

CHARACTERIZATION AND LIFECYCLE TESTING OF HYDRIDE COMPRESSOR ELEMENTS FOR THE PLANCK SORPTION CRYOCOOLER

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ABSTRACT

The Jet Propulsion Laboratory is developing two continuous 20 K nominal sorption-based coolers for the European Space Agency (ESA) Planck mission. Sorbent beds containing the hydrogen absorbing Lanthanum-Nickel-Tin alloy $\text{LaNi}_{4.78}\text{Sn}_{0.22}$ are being tested to evaluate their performance as compressor elements for unprecedented two years of flight operation. To provide basic characterization and life cycling data, we have developed a test facility that allows us to test three prototype compressor elements under all conditions expected for flight cooler operation. Each bed is continuously cycled over the temperature range between 280 K and about 470 K to follow the alternating absorption and desorption behavior of the hydride.

We present data on the hydrogen mass flow rates and thermal characteristics for all phases of the compressor cycle, with an emphasis on the controlled absorption of hydrogen. This function of the compressor element is crucial since it establishes the cold end temperature and stability of the cooler. We also present data obtained over thousands of temperature cycles from these beds to determine the extent of degradation of the compressor element performance from changes in the hydride sorbent or other sources. Finally, we discuss our future testing of a complete prototype cooler where six compressor elements will be used with a Joule-Thomson (J-T) cold end to provide continuous cooling at 18 – 20 K.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) is developing continuous cycle hydrogen sorption cryocoolers for ESA's Planck mission [1], which will launch in 2007. Two instruments, the

Low Frequency Instrument (LFI) and High Frequency Instrument (HFI), will measure the Cosmic Microwave Background (CMB) anisotropy. The sorption cooler will operate at a nominal temperature of 20 K with a cooling power of 1 W. The LFI will directly receive its cooling from the sorption cooler [2,3]. For the HFI, which operates at ~ 0.1 K, the sorption cooler will serve as a pre-cooling stage for the 4 K mechanical helium J-T cryocooler and an open-cycle helium dilution refrigerator [2].

Continuous cycle hydrogen sorption cryocoolers have been previously discussed by Freeman, et al. [4]. The requirements of the Planck mission necessitate extending the state-of-the-art for absorption cryocoolers in almost every aspect of performance [3]. Namely, mission lifetime requirements are for two years of cooler operation, which is a 100-fold increase over any previous hydrogen sorption cooler. The main component driving cooler lifetime is the hydride compressor element. In FIG 1 we show some typical isotherms for the $\text{LaNi}_{4.78}\text{Sn}_{0.22}$ alloy that were measured [5] before and after accelerated aging at elevated temperatures and pressures [6]. The hydride compositions where the pressures are relatively flat are commonly referred to as the “plateau” regions. It is the slope and width of these plateau regions that determines the fundamental design parameters of the cooler [7]. As is well known [8] the plateau regions will develop large positive slopes and will shrink as the hydride material undergoes the repeated heating and cooling necessary for cooler operation [3,4]. In addition, the middle of the plateau will shift to lower pressures [5,6]. These effects are shown in FIG 1 to be most pronounced at high temperature (pressure) and concentration conditions. These degradation effects must be understood and accounted for in the design of the Planck sorption cooler [3,7].

To this end, we have built a life cycle apparatus [9], which allows three prototype compressor elements to be cycled under the conditions of actual cooler operation. In addition to the effect of aging discussed above, we present controlled absorption data for a single compressor element. Before presenting this data, we give a discussion of compressor element cycle during cooler operation and a description of the apparatus being used to simulate this cycling.

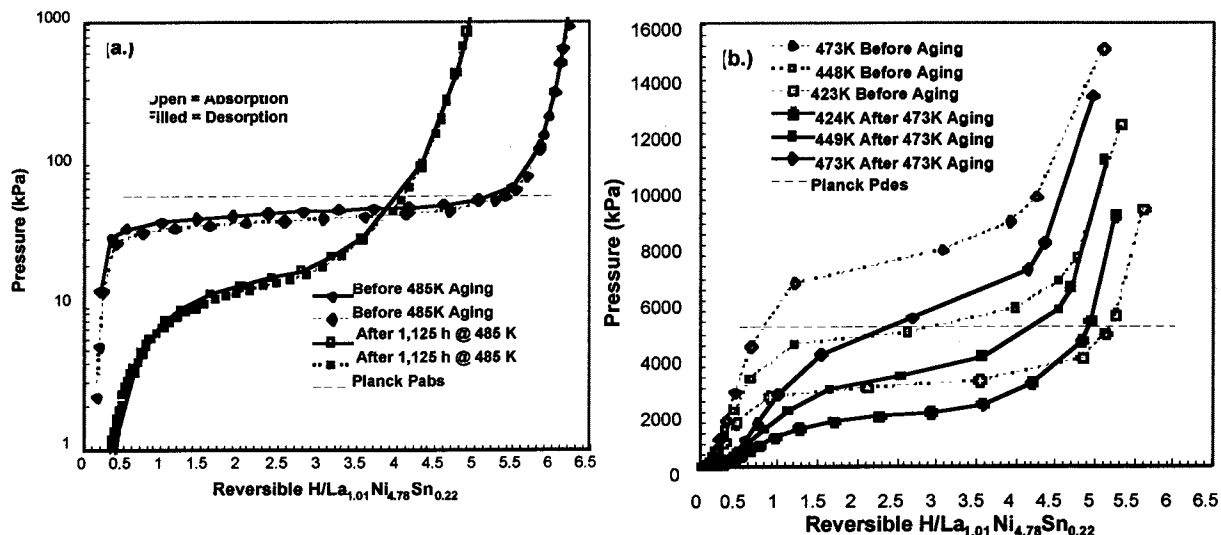


FIGURE 1. Representative hydrogen absorption and desorption isotherms for the $\text{LaNi}_{4.78}\text{Sn}_{0.22}$ alloy used to fill the Lifecycle Compressor Elements (LCE). (a) Isotherms determined at 300 K before and after aging at 485 K for 1125 h with pressure > 17.1 MPa and initial $x = 5.1$. (b) Desorption isotherms determined before (open symbols and dashed lines) and after aging (filled symbols and solid lines) at 473 K for 1425 h with pressure > 13.9 MPa and initial $x = 5.29$.

COMPRESSOR ELEMENT DESCRIPTION AND OPERATION

The Planck Lifecycle Compressor Elements (LCE) have been described in detail previously [9], thus only a brief summary is given here. In order to characterize differences due to workmanship three compressor elements (CEs) were built for this testing. Each CE consists of an inner cylindrical housing with the hydriding material $\text{LaNi}_{4.78}\text{Sn}_{0.22}$ distributed in an aluminum foam. The aluminum foam is used to reduce thermal gradients in the hydride material. A thermocouple and heater are located within this volume to measure the internal CE temperature and to heat the hydride material respectively. A concentric outer shell separates the inner vessel with a nominal 0.76-mm gap between the inner and outer shells. This gap serves as gap heat switch [3,10] to isolate and couple the beds to a constant temperature heat sink during a cooler cycle. For the “ON” state a gas pressure of ~10 Torr is introduced into the gap; the “OFF” state pressure is on the order of 10^{-3} Torr.

In the Planck sorption cryocooler, six compressor elements are used to provide high-pressure gas at 50 bar and 50 K for a Joule-Thomson (JT) expansion, which produces liquid into three liquid reservoirs [3]. Gas is then absorbed by three CEs in order to maintain the vapor pressure below the required 60 kPa (450 Torr). In order for cyclic operation four cycle phases are needed. These steps are: heatup, desorption, cooldown, and absorption. At any one time one CE is in the heatup, desorption, and cooldown phases. As stated above three CEs are in the absorption phase. During heatup, the CE is heated at constant power to generate a pressure of 5,066 kPa (50 atm) with the gas gap heat switch evacuated. During the desorption step, gas is released by a single bed at constant power with an average mass flow of 6.5 mg/s. Again the heat switch is off in this phase. In the cooldown phase, the heat switch is on and the CE is cooled to the heat sink temperature of ~270 K. Finally, three CEs absorb gas to maintain the liquid reservoirs at constant vapor pressure. The cycle time was chosen to be 667 s (667 s for the first three cycles and 2000 s for the absorption phase). The choice of cycle time is closely related to performance, power, and lifetime requirements for the cooler.

CHARACTERIZATION AND LIFECYCLE TEST FACILITY

The apparatus built for basic characterization, controlled absorption, and life cycling is shown schematically in FIG 2. The portion to the left of dashed line was used for basic characterization and life cycle testing. It has been described previously [9]. The portion to the right of the dashed line was added for controlled absorption measurements for CE #2. The basic apparatus allows us to reproduce the heatup, desorption, and cooldown cycles of an actual operating cooler. The absorption cycle is not faithfully reproduced during these lifecycle aging tests as the absorption of gas is not done at a constant mass flow, but is done by allowing the gas to flow into the element uncontrolled. As regards life cycling, and aging effects, the uncontrolled absorption will cause the temperatures and pressures to rise higher than for a controlled absorption where the hydrogen is absorbed over 2000 seconds. Thus, our life cycling operation is an upper bound on aging effects [9].

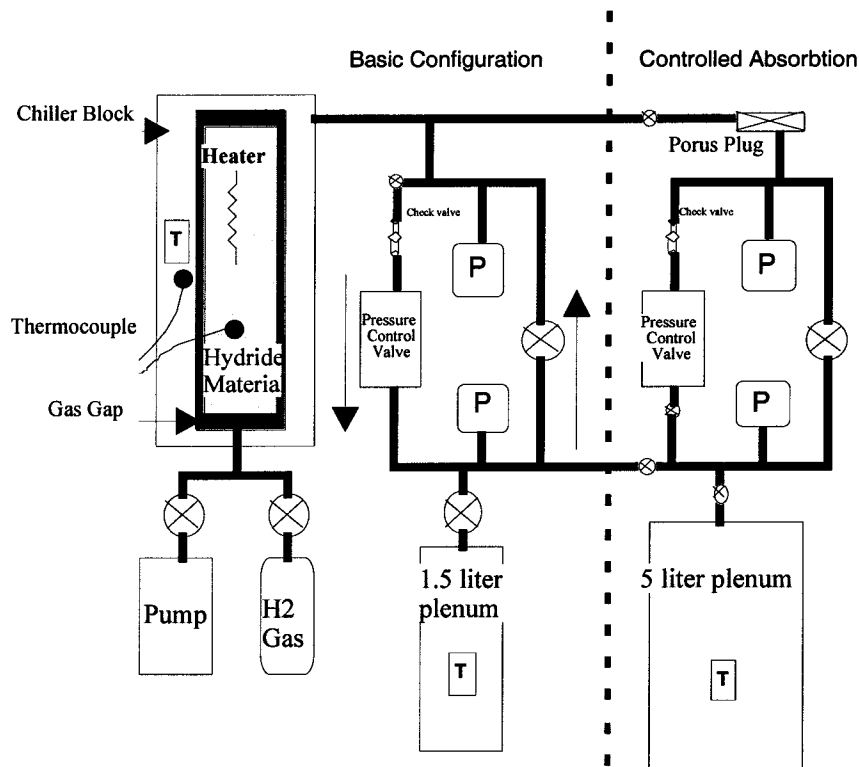


FIGURE 2. Schematic of testing apparatus. The basic configuration, to the left of the dashed line was used for lifecycle testing. The portion to the right of the dashed line is used only for CE-2 during controlled absorption.

For testing the three CEs are mounted into a vacuum bell jar on aluminum chiller plates. The bell jar is evacuated to a pressure of 10^{-4} Torr to simulate the operating conditions of the cooler. A water chiller maintains the chiller plates and the three CEs at a constant temperature when the three gas-gap heat switches are on. A Type K thermocouple measures the internal temperature of each CE. The reference junction of this thermocouple is thermally attached to the chiller block near a 100- Ω platinum resistance thermometer (PRT). The PRT measures the reference temperature for the CE thermocouple. Plumbing through the vacuum bell jar allows hydrogen filling/removal while the CEs are under vacuum. A common circuit with electropneumatic valves allows filling and evacuation of the three CE gas-gaps.

External to the vacuum bell jar, a pressure control valve [Brooks model 5866RT] in parallel with a electropneumatic valve separate the CEs from a 1.5 liter volume. The control valve uses an internal PID control to remain closed while a CE is being heated. When the upstream pressure reaches 50 atm the valve opens to maintain the upstream pressure constant at 50 atm. Hydrogen gas then flows into the 1.5 liter volume. The upstream (CE) pressure and the downstream pressure (1.5 liter tank) are measured using 1000 Psi capacitive pressure sensors [MKS model 850B]. Although the pressure control valve contains a mass flow meter, it was found that more accuracy was obtained by determining the mass flow from the time-rate-of-change of the downstream pressure sensor and the temperature using a PRT located on each 1.5 liter volume. For absorption a parallel electropneumatic valve is opened and the gas returns to the CE and the cycle is repeated.

As discussed above, additional capability was added in order to perform controlled absorption experiments on one of the CEs. This is depicted to the right of the dashed line in FIG 2. Instead of uncontrolled return of hydrogen gas to the CE bed during the absorption phase, a constant pressure is maintained downstream of a pressure control valve and upstream of a flow impedance. The flow impedance was found to give the nominal absorption mass flow rate, 2.17 mg/s, for an upstream pressure of 13 ATM. The five-liter volume shown in FIG 2 was needed to keep the pressure upstream of the flow controller above this value. The same 1000 Psi pressure sensors used in the basic configuration were used to measure these pressures. The pressure of the absorption bed was measured using a 1000 Torr (MKS model 626) capacitive manometer sensors. The mass flow was determined by the time-rate-of-change of pressure in the 5-liter tank. A PRT is used to provide the temperature for this calculation.

All of the above sensors are measured and recorded by Labview software. The CE heaters and electropneumatic valves are also controlled by this software.

BASIC COMPRESSOR ELEMENT CHARACTERIZATION

To begin testing, each of the three CEs is charged to an initial hydrogen composition $\text{LaNi}_{4.78}\text{Sn}_{0.22}\text{H}_{5.3}$. The bell jar is evacuated and each chiller plate is brought to 280 K. Each gas-gap is filled with 30 Torr of hydrogen gas to equilibrate each CE to its chiller plate. After the internal temperature of the CEs has reached 280 K, the gas-gap is evacuated and power is applied to each CE heater. Several iterations are made until the power to bring each CE to 50 atm in 667 s. After the heatup power is obtained the desorption power is determined. This is done by finding the power that transfers 4.3 grams of hydrogen gas to the 1.5 liter tanks. This is equivalent to an average mass flow of 6.5 mg/s for 667. After the heatup and desorption powers are determined a complete cooler cycle can now be performed.

Figure 3 shows temperature and pressure data for a complete cycle while Figure #? Shows mass flow and power for the same cycle. The heatup and desorption powers are summarized in Table 1. As can be seen from Figure # the temperature for CE-1 during both heatup and desorption is larger than for CE-2 and CE-3 which have similar temperature behavior during the two phases. In addition, the desorption powers for the three CEs vary, with CE-1 needing

Compressor Element	Heatup Power (W)	Desorption Power (W)
CE-1	175	157
CE-2	174.9	149
CE-3	174.8	143

TABLE 1. Power levels used for cycling.

the most power. We attribute these differences to hydride distribution, which results in larger temperature differences in CE-1 than for the other two beds. Although CE-2 and CE-3 have similar temperature profiles the desorption power for CE-3 is 6 W lower than for CE-2. This is the same order as the 8 W difference between CE-1 and CE-2. We conclude from this that the behavior of the CE thermocouple is not an accurate measure of the hydride distribution.

This is not surprising in that the thermocouple is a local measurement. In spite of these basic variations between CEs, each of these elements would satisfy design requirements.

CONTROLLED ABSORPTION RESULTS

As discussed above, during absorption the CEs must maintain the vapor pressure below 450 Torr for 2000 seconds at a mass flow of 2.17 mg/s for a nominal chiller temperature of 270 K. Figure 4a) shows pressure and temperature data for CE-2 under these conditions. As marked in Figure, the pressure has reached approximately 260 Torr after 2000 seconds. In

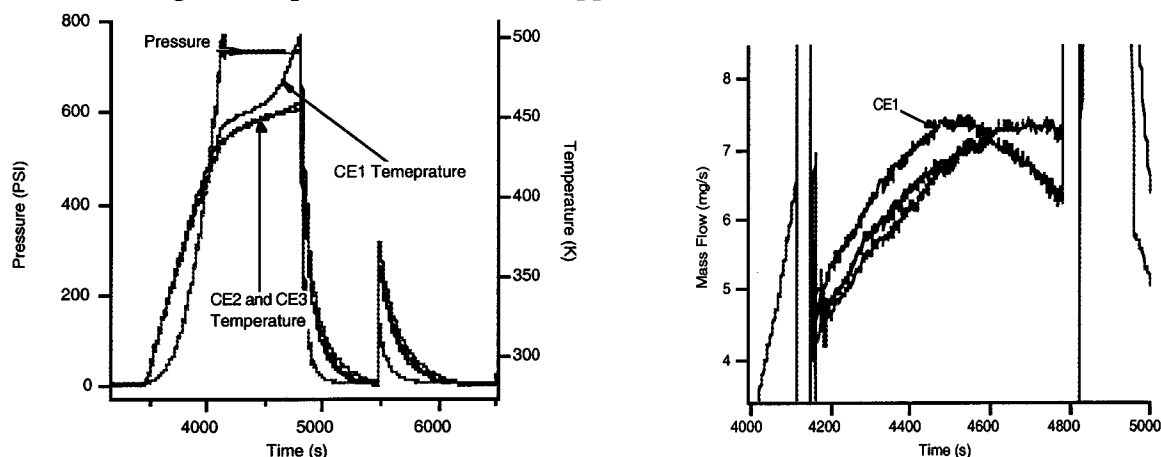


Figure 3. a) Plot shows the pressure and temperature behavior for a typical testing cycle for the three CEs. b) Plot shows mass flow behavior for this same cycle.

Figure is shown controlled absorption at a mass flow of 6 mg/s. After only 450 seconds the bed pressure has exceeded the required 450 Torr. At these high mass flows the heat of adsorption cannot be removed from the system quickly enough. This is the reason that 3 CEs are used for the absorption process. Data was obtained for other chiller temperatures with 270 being the highest temperature at which the above requirements could be meet.

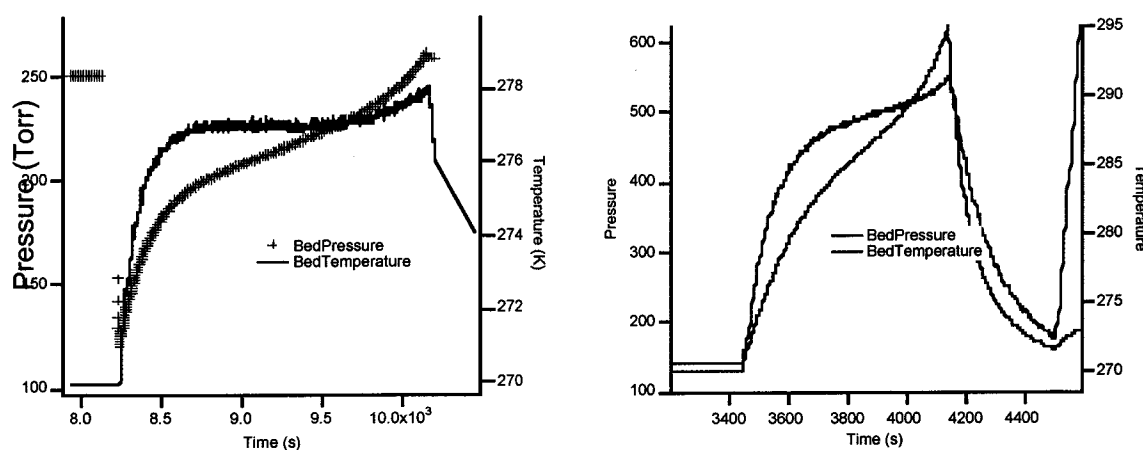


Figure 4. a) Plot shows temperature and pressure data for CE-2 controlled absorption cycle. Here the mass flow is 2.17 mg/s. b) Plot is for a mass flow of 6 mg/s.

LIFECYCLE RESULTS

After the above measurements the three CEs began long term cycling. Cycling began with the heatup and desorption powers given in Table 1. CE-1 and CE-3 underwent 5000 cycles and 3000 cycles for CE-2. CE-2 was removed from cycling so that equipment could be used for other testing. To increase the amount of cycles it was decided to decrease the absorption cycle time from 2000 to 1000 which results in a 3000 second total cycle. As discussed above, the 2000 second desorption cycle is done so that the pressure of the CE remains below 450 Torr. For

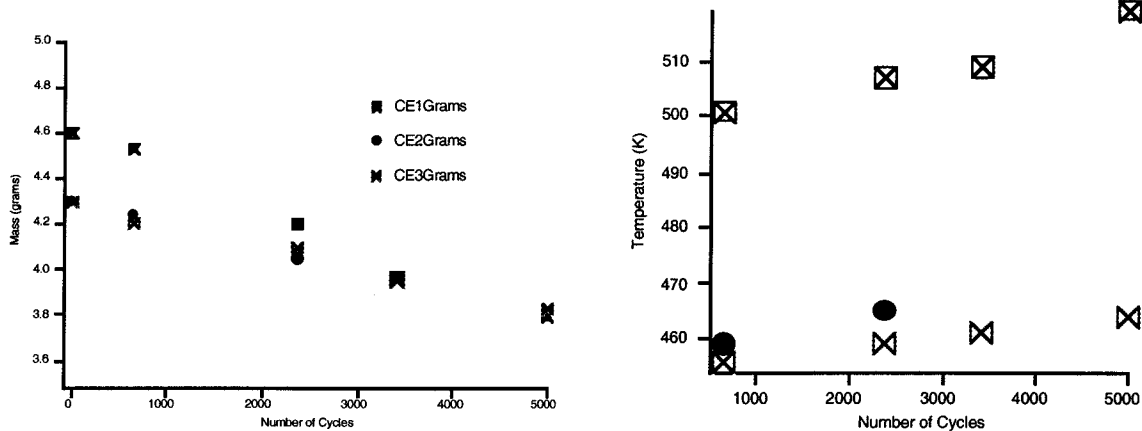


FIGURE 5. a) Plot is of the total mass desorbed by each CE as a function of cycle number. b) Plot is of the final desorption temperature as a function of cycle number.

our cycling data we use an uncontrolled absorption, so the only requirement is that the CE return to the chiller temperature in the shortened 1000 cycle time. This indeed is the case. A two year mission is equivalent to $\sim 15,800$ cycles. Thus, CE-1 and CE-3 cycled for almost 1/3 of the mission life, while for CE-2 it has cycled for 1/5 of the mission life. During this cycling the power levels were kept at values given in Table 1. As discussed above, the fundamental effect on cooler performance is to increase the power during the desorption cycle. For our testing, where the desorption power is held constant, we should see a decrease in the amount of mass transferred during the desorption cycle.

CONCLUSIONS

Detailed characterizations have been performed on three prototype compressor elements for the Planck sorption cryocooler. Further evaluations are continuing on these units to better define any performance limitations and sources of degradation or failures through more cycles than predicted for the flight units. This information will be incorporated in the final designs and fabrication of the Planck flight sorption coolers.

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